

The origin of the broad line region in active galactic nuclei

Bożena Czerny and Krzysztof Hryniewicz

Nicolaus Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland

ABSTRACT

Aims. Although broad emission lines are the most reliable signature of the nuclear activity of a galaxy and the location of the emitting material is well measured by the reverberation method, the physical cause of the formation of the broad line region remains unclear. We attempt to place some constraints on its origin.

Methods. We study the properties of the accretion disk underlying the broad line region.

Results. We find that the effective temperature at the disk radius corresponding to the location of the broad line region, as inferred from the $H\beta$ line, is universal in all monitored sources and equal to 1000 K. This value is close to the limiting value that permits for the existence of the dust.

Conclusions. The likely origin of the low ionization part of the broad line region is the strong local dusty wind from the disk. This wind becomes exposed to the irradiation by the central regions when moving higher above the disk surface and subsequently behaves like a failed wind, thus leading to a local mixture of inflow and outflow. This may provide the physical explanation of the turbulence needed both to smooth the line profiles as well as provide additional mechanical heating.

Key words. galaxies: quasars: general - galaxies: nuclei - galaxies: Seyfert

1. Introduction

Broad emission lines in the optical and UV band are the basic signature of active galactic nuclei and have been extensively studied for more than 50 years. These studies have allowed several key properties of the BLR to be identified: (i) the emitting medium is located close to the accretion disk powering the AGN activity, and rarely crosses the line of sight towards the nucleus; (ii) the medium is predominantly in Keplerian motion with additional velocity components (e.g., Done & Krolik 1996; Kollatschny 2003; Collin et al. 2006); (iii) the outer edge of the BLR is delineated by the dusty/molecular torus (Netzer & Laor 1993, Suganuma et al. 2006); and (iv) the existence of BLR is likely to actually require the existence of the cold disk (e.g. Nicastro et al. 2003, Czerny et al. 2004, Cao 2010). However, major uncertainties about the geometry, dynamics, and physics of BLR still remain unknown (for a review, see e.g. Sulentic et al. 2000, Gaskell 2009).

There is no such clear consensus on the mechanism determining the inner radius, or effective radius, of the BLR. The monitoring of over 30 AGN has shown that, when the contribution to the optical flux of the host galaxy is accounted for, there is a simple power-law relation between the BLR radius, as measured by the $H\beta$ line, and that the optical monochromatic luminosity, and the index of the power law is almost exactly equal 0.5, as expected by simple ionization models.

The reason why this particular luminosity-dependent radius is chosen by the sources remains unclear because reverberation studies have not yet returned information on the 3-D space density and velocity structure. There are several general suggestions of a wind type outflow that either covers a large range of disk radii (Murray et al. 1995; Elitzur

& Shlosman 2006, Elitzur 2008), or mostly covers a narrow radial range (Elvis 2000, Risaliti & Elvis 2010), with a specific suggestion that the BLR forms at the radius where the gas pressure becomes comparable to the radiation-pressure. The wind outflow is expected to be either radiation pressure driven, or magnetically driven.

One aspect of the BLR scaling is, however, surprising. Among the reverberation-studied objects, there are both Seyfert 1 galaxies and narrow line Seyfert galaxies. The SEDs of the two types of sources, when normalized at 5100 Å flux, are different, including an expected difference in the ionizing flux (e.g. Wandel & Boller 1998). Nevertheless, there seems to be no clear difference in the BLR scalings of the two classes of objects, although the overall dispersion is large. We attempt to explain this phenomenon in the present paper.

2. The BLR scaling law and the accretion disk

The scaling of the BLR with luminosity discovered by Kaspi et al. (2000) has been studied by several authors (e.g. Peterson et al. 2004). Here we use the result of Bentz et al. (2009), where the starlight contamination was carefully removed. The power-law index in the scaling between the BLR size and the monochromatic luminosity in their analysis is consistent with 0.5 within the errors. We thus fixed this slope at 0.5, and refitted their data again, obtaining the relation

$$\log R_{BLR}[H\beta] = 1.538 \pm 0.027 + 0.5 \log L_{44,5100}, \quad (1)$$

where $R_{BLR}[H\beta]$ is in light days and $L_{44,5100}$ is the monochromatic luminosity at 5100 Å measured in units of 10^{44} erg s⁻¹. The value 0.027 is the error in the best-fit vertical normalization; the dispersion around the best fit is larger but still small at 0.21.

Send offprint requests to: e-mail: krhr@camk.edu.pl

We assume that the disk is not strongly irradiated, and the outflow from the disk is not too strong, so the simple theory of the alpha-disk (Shakura & Sunyaev 1973) applies. In this case, the monochromatic flux at 5100 Å can be calculated from the model, if the black hole mass and the accretion rate are known. Taking the numerical formula of Tripp et al. (1994) (corrected for a factor-of-two error, Nikolajuk, private communication), we derive

$$\log L_{44,5100} = \frac{2}{3} \log(M\dot{M}) - 43.8820 + \log \cos i, \quad (2)$$

where the black hole mass, M , and the accretion rate, \dot{M} , are in g and g s^{-1} , respectively. This formula allows us to calculate the BLR radius from the Eq. 1, if the product of $(M\dot{M})$ is known.

We now consider the effect of the inclination angle, i , on the measurements of the observed monochromatic flux, as well as the observed time delays. The estimate of the torus opening angle by Lawrence & Elvis (2010) implies that the average value of the inclination angle of a broad line object is $i = 39.2^\circ$, and we use this same value for all objects. We also assume that the reflection comes predominantly from the part of the BLR behind the black hole, thus the measured time delay is related to the disk radius, r , underlying BLR using the formula

$$r = \frac{R_{BLR}[\text{H}\beta]}{1 + \sin i}. \quad (3)$$

The Shakura-Sunyaev accretion disk theory allows us to calculate the effective temperature of the disk at that radius

$$T_{eff} = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma_B} \right)^{0.25} \quad (4)$$

where σ_B is the Stefan-Boltzmann constant. Since BLR is far from the central black hole, the factor representing the inner boundary condition (including a spinning or non-spinning black hole) can be neglected.

When we combine Eqs. 1, 2, 3, and 4, the dependence on the unknown mass and accretion rate vanishes, and we obtain a single value for all the sources in the sample

$$T_{eff} = 995 \pm 74 \text{ K}, \quad (5)$$

where the error reflects the error in the constant in Eq. 1.

This value is interesting since it is close to the critical temperature at which the dust can form. The distance is smaller than the distance to the dusty torus $R_{dust} \sim 0.4L_{45}^{1/2}$ pc (Nenkova et al. 2008; where L_{45} stands for the bolometric luminosity in $10^{45} \text{ erg s}^{-1}$) since in our case the temperature results only from the local disk dissipation instead of the irradiation by the central parts of AGN.

3. Application to separate objects

To assess the dispersion around this quantity in the Bentz et al. sample, we repeated the analysis using the individual measurements of the time delay and the monochromatic starlight-subtracted 5100 Å luminosity provided by Bentz et al. (2009) in their Table 8. We also separately studied a single source - NGC 5548 - since it had been monitored

extensively over a number of years and 14 annual measurements for this source are available.

We obtain the effective temperature of the disk related to BLR as before, for each measurement independently, converting the delay into the BLR radius, and then disk radius (see Eq. 3, as we assume the same geometrical factor for all sources) using Eqs. 2 and 4. The results are given in Table 1.

The average value of the disk temperature obtained from the 48 measurements (all apart from NGC 5548) is

$$T_{eff} = 1030 \pm 61 \text{ K} \quad (6)$$

and the dispersion in the measurements is 411 K for that sample.

Independently, we calculated the underlying disk temperature for the 14 measurements of NGC 5548 (see Table 1). In this case, the average temperature was

$$T_{eff} = 956 \pm 56 \text{ K}, \quad (7)$$

with a dispersion 210 K. These values are fully consistent with the previous value inferred directly from the scaling law.

We note that the dispersion in the measured value of the temperature is very low, only 0.16 in the logarithmic scale, comparable to the dispersion in the constant in Eq. 1.

We checked whether the disk temperature underlying the BLR correlates with any AGN parameter. For that purpose, we used the broad-band data fits for most of the monitored objects, provided by Vasudevan & Fabian (2009). Since there was no one-to-one correspondence between several delay measurements and broad-band spectra measurements, in this case we used the mean delays measured for a given object from Bentz et al. (2009) and the mean values of the bolometric luminosity from Vasudevan & Fabian (2009). The results for the disk temperature did not differ from those obtained from all measurements ($T_{eff} = 1029 \pm 88$ K, with dispersion 441 K). As expected, there is no correlation between the disk effective temperature and any other parameter, e.g., the black hole mass, the bolometric luminosity, and the Eddington ratio (the correlation coefficient was equal to -0.16, 0.08 and 0.26, respectively).

We also calculated the ionizing flux for all of these sources, using the broad-band spectrum from Vasudevan & Fabian (2009). For all the broad-band spectra, we calculated the ratio of the bolometric luminosity above 1 Ry to the monochromatic luminosity at 5100 Å. This dimensionless parameter accurately characterizes the expected differences in the ionizing properties of continua in these sources. Our results are given in Table 2. The average ratio is equal to 6.44 ± 0.78 , but the dispersion is large (4.8). If this ratio is given in log space, the dispersion is equal to 0.40.

Therefore, the dispersion in the logarithm of the ionizing flux in those sources is much larger than the dispersion in the scaling with monochromatic luminosity, 0.21, as well as the dispersion in the logarithm of the underlying disk temperature, 0.16. The ratio is also systematically higher for NLS1 galaxies (10.6 ± 2.6) than for S1 objects (5.5 ± 0.7). Interestingly, there seems to be a weak positive correlation between this ratio and T_{eff} .

Table 1. Effective temperature of the disk underlying BLR for sources from the reverberation sample. Bolded values were computed from mean time delays from Bentz et al.

Name	T_{eff} [K]	Name	T_{eff} [K]
Mrk 335	1302	PG 1226+032	986
	1731	PG 1229+204	662
1427		NGC 4593	1890
PG 0026+129	903	PG 1307+085	838
PG 0052+251	913	IC 4329Ab	683*
Fairall 9	1516	Mrk 279	1227
Mrk 590	951	PG 1411+442	575
	835	PG 1426+015	748
	605	Mrk 817	1203
	783		1274
749			707
3C 120	962		990
Ark 120	724	PG 1613+658	1607
	648	PG 1617+175	756
808		PG 1700+518	828
Mrk 79	1859	3C 390.3	934
	1318	Mrk 509	587
	1245	PG 2130+099	1836
1307		NGC 7469	2408
PG 0804+761	690	NGC 5548	828
PG 0844+349a	1181		694
Mrk 110	913		940
	1109		968
	633		1068
897			1094
PG 0953+414	858		864
NGC 3227	1058		987
	901		792
787			788
NGC 3516	995		772
NGC 3783	1020		1481
NGC 4051	584		825
NGC 4151	550		1289
PG 1211+143	826		859

* time delay taken from the Winge et al. (1996).

4. Discussion

The observed scaling between the size of the BLR and the square root of the monochromatic flux at 5100 Å measured according to the response of H β to the continuum works surprisingly well, although the ionizing flux is not expected to be proportional to the monochromatic optical flux because of observed variety of SED shapes.

Using a simple analytic formula, we have demonstrated that the observed scaling corresponds to a fixed-temperature, non-irradiated Shakura-Sunyaev disk, independent of the black hole mass and accretion rate. This temperature is about 1000 K, as derived for several sources, and in agreement with the value obtained directly from the BLR scaling by Bentz et al.

It is thus likely that the BLR forms when the local disk effective temperature becomes low enough for dust to form in the disk atmosphere and the locally driven massive outflow to develop, similar to the outflows observed from stars at the asymptotic giant branch. The pressure in the disk atmosphere, calculated with the code for the vertical disk structure (Rozanska et al. 1999), provides the conditions required for dust formation discussed by Elvis et al. (2002). However, this wind cannot achieve large heights, in contrast to stellar winds, since at larger heights the wind is

Table 2. The dimensionless ratio of the luminosity above 1 Ry to the monochromatic luminosity at 5100 Å. LR is defined as $L_{1\text{Ry}-100\text{keV}}/\lambda L_\lambda(5100\text{\AA})$

Name	LR	Name	LR
3C 120	7.89	NGC 4051 (2)	11.29
3C 390.3	8.28	NGC 4151 (1)	7.92
Akn 120	2.92	NGC 4151 (2)	7.97
Fairall 9	2.34	NGC 4151 (3)	9.04
Mrk 110	13.33	NGC 4593	15.59
Mrk 279 (1)	8.71	NGC 5548	4.09
Mrk 279 (2)	9.10	NGC 7469	14.35
Mrk 279 (3)	8.73	PG 0052+251	2.91
Mrk 335 (1)	13.89	PG 0844+349	6.48
Mrk 335 (2)	23.14	PG 0953+414	4.07
Mrk 509	3.17	PG 1211+143 (1)	3.16
Mrk 590	6.75	PG 1211+143 (2)	2.56
Mrk 79	5.12	PG 1226+023	4.76
NGC 3227 (1)	6.28	PG 1229+204	4.34
NGC 3227 (2)	4.13	PG 1307+085	1.27
NGC 3516	2.10	PG 1411+442	0.37
NGC 3783 (1)	4.97	PG 1426+015	0.54
NGC 3783 (2)	4.05	PG 1613+658	1.92
NGC 4051 (1)	6.49	PG 2130+099	0.60

irradiated by the central source and the dust at these radial distances cannot exist, as this region is not yet at the distance of the dusty torus. Therefore, the material, initially accelerated very efficiently, may partially fall back owing to a decrease in the driving force. This would indicate that the BLR - or at least the low ionization line (LIL) part of it (Collin-Souffrin et al. 1988) - may consist of material, roughly in Keplerian motion, but with clumps still outflowing and clumps flowing down. This chaotic motion will smear the expected disk-like emission-line profile equally efficiently as in the assumption of a very extended flow, without producing considerable asymmetry. We visualize the BLR geometry in Fig. 1.

This picture of a 'boiling' BLR region is consistent with two main lines of arguments, which have already been discussed in the literature. First, the observational arguments for both inflow and outflow in BLR were given in a number of papers (e.g. Done & Krolik 1996, Elvis 2000, Ferland et al. 2009, Gaskell 2009; Shapovalova et al. 2010). Second, there has been considerable discussion of the heating efficiency of the LIL BLR: radiative heating seems too low compared with the observed radiation field, and additional mechanical heating seems to be required (Collin-Souffrin et al. 1988, Bottorff & Ferland 2002, Shapovalova et al. 2004, Shapovalova et al. 2010).

Our scenario of local dust-driven wind with subsequent dust evaporation and inflow provides a physical basis for the development of this turbulent medium, with considerable velocity dispersion superimposed on the overall Keplerian motion of the underlying disk.

This scenario can be quantitatively compared with alternative suggestions that the onset of the BLR region is due to (i) the transition from the radiation pressure to gas pressure within the disk (Nicasio 2000) or (ii) the transition from non-self-gravitating to self-gravitating disk structure (Collin & Hure 2001). If the first option is the true underlying mechanism, we can estimate the position of this transition using the Shakura & Sunyaev (1973) results. The transition takes place at the radius R_{ab} scaling

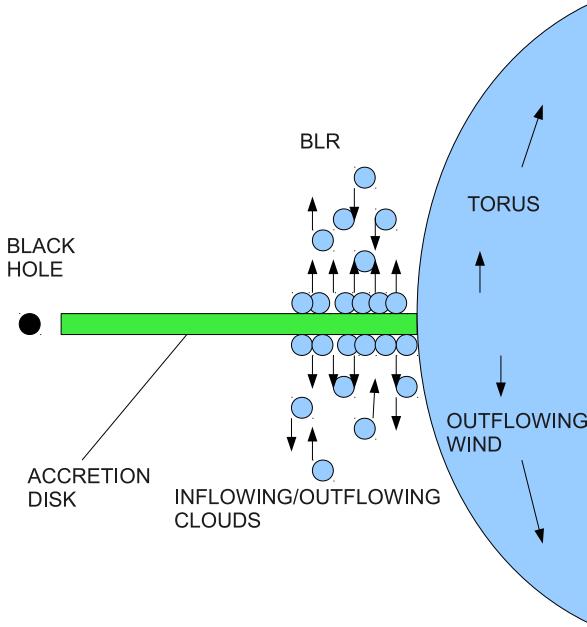


Fig. 1. The BLR region covers the range of the disk with an effective temperature lower than 1000 K: the dusty wind rises and then breaks down when exposed to the radiation from the central source. The dusty torus is the disk range where the irradiation does not destroy the dust and the wind flows out.

as $M^{23/21}\dot{m}^{16/21}$ (in cm, not in gravitational radii), where \dot{m} is the accretion rate in Eddington units. We can relate the black hole mass to the monochromatic luminosity again using the formula from Tripp et al. (1994). Thus, the expected scaling of the BLR radius in this scenario can be represented as

$$R_{BLR}^{radpres} \propto L_{5100}^{23/28} \dot{m}^{3/14}, \quad (8)$$

such that the slope of the dependence on L_{5100} is considerably steeper than 0.5, but not much steeper than for previous results inferred from the reverberation mapping.

In the case of the self-gravity transition, we can estimate the transition radius using the simple criterion that the local disk density should be equal to GM/r^3 . But since this region may occur in either region (b) or (c) (see Shakura & Sunyaev 1973 for the definitions and analytic expression for the density), we have to calculate the expected trend for the two regions separately, obtaining

$$R_{BLR}^{sg} \propto L_{5100}^{1/36} \dot{m}^{-83/54} \quad (\text{region b}),$$

$$R_{BLR}^{sg} \propto L_{5100}^{-7/60} \dot{m}^{-37/90} \quad (\text{region c}), \quad (9)$$

so in both cases the dependence on the monochromatic luminosity differs strongly from our model. There is also an additional dependence on the accretion rate, which is weak (and positive) for the radiation pressure/gas pressure scenario, but much stronger for the self-gravity onset scenario. Monitoring results covering an even broader dynamical range of luminosity may be required to definitively rule out any of those alternative scenarios.

Within the framework of our BLR model, we can also estimate the radial size of the BLR, assuming that it covers the region from the radius where $T_{eff} = 1000\text{K}$ to the

beginning of the dusty torus, $R_{dust} \sim 0.4L_{45}^{1/2}$ pc (Nenkova et al. 2008). The ratio of the two radii can be expressed in terms of the black hole mass, the accretion rate, and the accretion flow efficiency η ($L_{bol} = \eta \dot{M} c^2$)

$$\frac{r_{1000K}}{R_{dust}} = 0.03 \frac{M_8^{1/6}}{\dot{m}^{1/6} \eta_{0.1}^{1/2}}, \quad (10)$$

where the black hole mass is expressed in $10^8 M_\odot$, and the efficiency in units of 0.1. Since the dependence on the black hole mass and the accretion rate is generally weak, in high accretion efficiency sources the outer radius is larger by a factor of 30 than the inner radius. However, if the accretion rate drops by a factor of 10^{-3} , and, more importantly, the accretion efficiency drops by a factor of 100, then in our model the BLR is expected to reduce to a narrow ring ($r_{1000K} \approx R_{dust}$). It is possible that this is the basic explanation of the relatively narrow BLR in several broad-line radio galaxies with clearly visible double peaks in the $H\beta$ line (see e.g. Lewis et al. 2010 and the references therein).

If indeed the scenario outlined in the present paper is a correct interpretation, it means that magnetic wind outflow is not the dominant mode of outflow from the disk. On the other hand, this type of outflow is still likely to be present, perhaps being responsible for finally driving some material far away from the disk where high ionization lines form.

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